

HAWAII AND GALE CRATER: A MARS ANALOGUE STUDY OF IGNEOUS, SEDIMENTARY, WEATHERING, AND ALTERATION TRENDS IN GEOCHEMISTRY

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Introduction: Sedimentary rocks in Gale Crater on Mars indicate a varied provenance with a range of alteration and weathering [1, 2]. Geochemical trends identified in basaltic and alkalic sedimentary rocks by the Alpha Particle X-ray Spectrometer (APXS) on the Mars rover *Curiosity* represent a complex interplay of igneous, sedimentary, weathering, and alteration processes. Assessing the relative importance of these processes is challenging with unknown compositions for parent sediment sources and with the constraints provided by *Curiosity*'s instruments. We therefore look to Mars analogues on Earth where higher-resolution analyses and geologic context can constrain interpretations of Gale Crater geochemical observations.

We selected Maunakea (AKA Mauna Kea) and Kohala volcanoes, Hawai'i, for an analogue study because they are capped by post-shield transitional basalts and alkalic lavas (hawaiites, mugearites) with compositions similar to Gale Crater [1, 3]. Our aim was to characterize Hawaiian geochemical trends associated with igneous processes, sediment transport, weathering, and alteration. Here, we present initial results and discuss implications for selected trends observed by APXS in Gale Crater.

Methods: We sampled fresh and altered lavas from basaltic, hawaiitic, and mugearitic flows on Maunakea and Kohala. Weathering profiles were sampled at roadcuts where a range of unaltered to highly weathered material was exposed. To evaluate sedimentary mixing, we collected outwash sand and gravel samples at various elevations. To emulate APXS measurements, bulk powders were prepared from cm-scale hand samples and analyzed by standard XRF methods. Sampling cinder cones and elevations >3700 m was not permitted; we report previous results on unaltered and altered materials from these sites [4], and from an acid sulfate alteration profile of a Kilauea basalt [5].

Results: Igneous compositions fall into the post-shield compositional classes of transitional basalt, hawaiite, and mugearite, with alkali content increasing in the younger, more evolved flows. Outwash sediment spans the same range, but also fills the igneous compositional gap between basalts and hawaiite/mugearites. Weathering and alteration trends fall into two groups defined by [4]: hydrolytic and acid sulfate.

Hydrolytic alteration is apparent in weathering profiles and palagonitized tephra, and is characterized by mobilization of $K \geq Na > Ca > Mg > Si$ and conservation

of Ti, Al, and Fe (Fig. 1a, b, c). Volatile content is high (LOI >1 wt%) but SO₃ content is low (<0.2 wt%).

Acid sulfate alteration leads to low pH mobilization of Mg, Mn, Fe, Al, and Ca, while Si and Ti are retained (Fig. 1d, e) and SO₃ is usually added (>1 wt%). Potassium tends to accumulate in secondary sulfates (Fig 1d). In both alteration regimes, variable leaching of some elements indicates open systems.

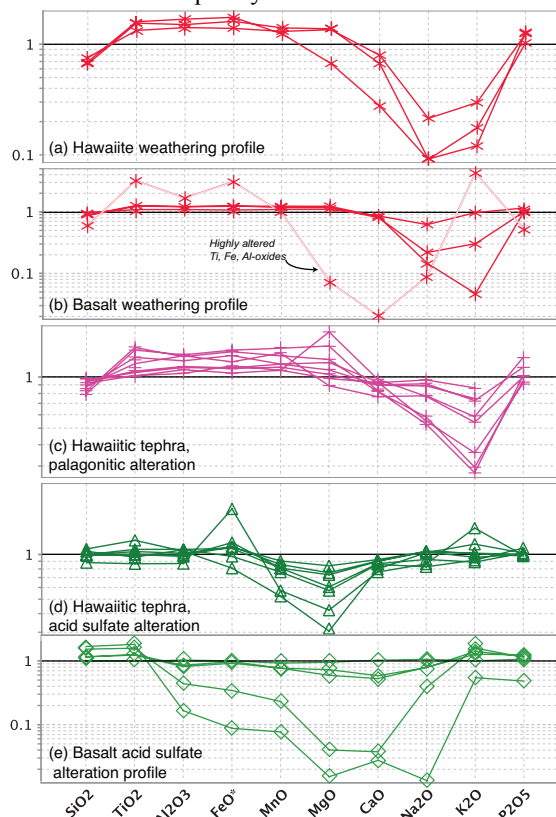


Fig. 1: Oxide ratios of altered Hawaiian samples relative to the unaltered parent. Data from (c, d) and (e) are from [4] and [5], respectively.

Discussion: *Gale Crater analogue.* The Mars surface environment (e.g., dust) complicates our ability to distinguish between alteration regimes. In particular, addition of SO₃ is characteristic of acid sulfate alteration [4], but elevated SO₃ in Martian dust and possible Ca-sulfates in cement/detritus may obscure the signal. In addition, Na and Mg have contrasting solubilities during acid sulfate and hydrolytic alteration (Fig. 1), but concentrations of these elements determined by APXS are

most affected by dust on rock surfaces [6]. Lastly, identifying mobile elements and mass gain/loss in Gale with altered rock/parent ratio plots (Fig. 1) is not possible because parent compositions are presently unknown. We thus use element variation diagrams (Figs. 2, 3) to compare known process vectors on Hawai'i with geochemical trends identified among Gale datasets.

Igneous trends and sedimentary mixing in the Bradbury Group. The similarity of Bradbury Group sedimentary rocks to post-shield volcanics [3, 6] is evident in correlation with alkali feldspar content (AF control line; Fig. 2a, c). Gale is distinct from Hawai'i, however, having a K-rich component (Bathurst_Inlet) consistent with addition of K-feldspar (KF; Fig. 2 b, d). Elevated alkalis among Bradbury sediments indicate that any hydrolytic open system weathering was limited (Fig. 2c). Magnesium is also high in these sediments, which is not consistent with open system acid sulfate alteration (Fig. 3). Closed system and incipient alteration may not be discernible in the bulk oxides [e.g., 7].

Bradbury group sediments span the igneous compositional gap between Hawaiian basalts and hawaiite/mugearites [8]. Hawaiian outwash sand and gravel, which are a product of mechanical mixing, fill this gap and provide an analogue explanation of igneous endmember mixing (Fig. 2a, b). The Gale sediment source likely contains three igneous endmembers (Fig. 2d): (1) basaltic (YKB), (2) mugearitic (JakeM), and (3) potassic (Bathurst_Inlet). Intermediate compositions (Alkalic other) indicate physical mixing of the three endmembers during transport to the crater floor.

Acid sulfate alteration trends in the Stimson and Murray Fms Fracture associated, high silica haloes discovered in Lower Mt. Sharp strata are thought to form by acid sulfate alteration in Gale [2]. Dramatic decreases in metals (e.g., Ni, Zn) and elevated SiO₂ and TiO₂ among Stimson and Murray haloes are similar to trends linked to localized acid sulfate alteration on Hawai'i (Figs. 1e, 3a). The composition of the Stimson Fm is similar to relatively unaltered soil and falls along the mafic/felsic igneous mineral trend in a plot of Mg/Si vs. Al/Si (Fig 3b). In contrast, Stimson haloes trend toward the origin as Mg and Al decrease relative to Si, such as is seen among open system acid sulfate altered basalt from Kilauea (Fig. 3a) [5].

Extending the acid sulfate alteration interpretation to the Murray Fm is plausible [9]. The Murray Fm is elevated in SiO₂ and TiO₂ and is depleted in most metals, similar to the Stimson fracture haloes and Hawaiian acid sulfate alteration (Fig. 3). Murray silica enrichments, however, may in part result from volcanic tridymite [10], a component that underlines the complexity of the Murray Fm.

Conclusion: Hawai'i has been studied as a Mars analogue by multiple workers, and the discovery of high

alkali mugearites has reinforced the usefulness of Maunakea and Kohala for this purpose. We are currently expanding on the work presented here to include mineralogy and an APXS analytical analogue: proton-induced X-ray emission (PIXE) spectrometry. We will examine what may be resolvable by *Curiosity's* APXS and ChemMin instruments to help understand Gale's basaltic-alkalic sedimentary landscape.

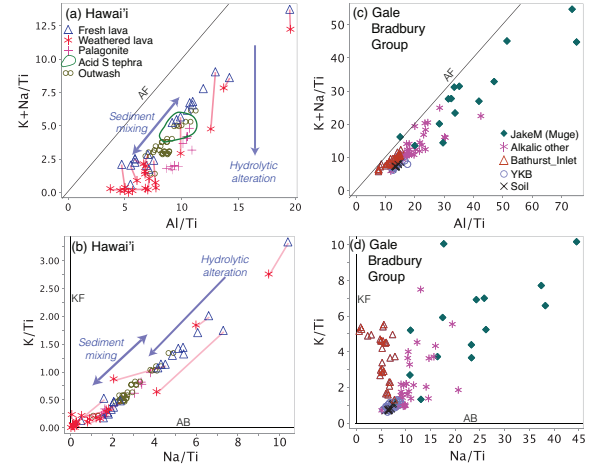


Fig. 2: Molar alkali plots of (a, b) Hawaiian samples and (c, d) the Bradbury group in Gale. Red tielines connect weathering profiles. Vectors indicate mixing and alteration trends. Alkali feldspar control lines are shown (AF, KF, AB).

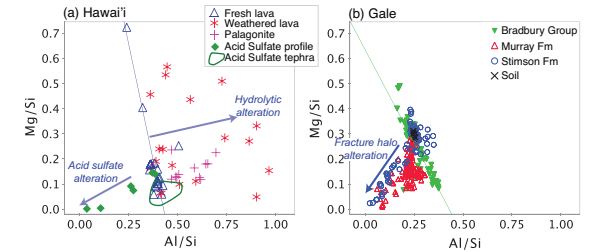


Fig. 3: Variation of Mg/Si and Al/Si at (a) Hawai'i and (b) Gale. Lines indicate a mafic/felsic igneous trend; deviation from this trend is consistent with open system alteration (arrows).

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References: [1] Thompson et al., 2016, JGR-Planets. [2] Yen et al., 2016, 47th LPSC. [3] Stolper et al., 2013, Science. [4] Morris et al., 2000, JGR-Planets. [5] Morris et al., 2000, LPSC. [6] Schmidt et al. 2014, JGR-Planets. [7] McLennan et al., 2013, Science. [8] Wolfe et al., 1997, USGS 1557. [9] Rampe et al., accepted 2016, EPSL. [10] Morris et al, 2016, PNAS.